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TECHNICAL REPORT

WHITE OAK LABORATORY

1/f NOISE IN AMORPHOUS GeTe

BY
K. Peter Scharnhorst

18 JUNE 1976

NAVAL SURFACE WEAPONS CENTER
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An experiment designed to determine the 1/f noise power of amorphous semiconductors in the presence of electrode noise is described. Results of measurements of the room temperature current noise power spectral density of amorphous GeTe are presented. Our data to date indicate that bulk 1/f noise in a-GeTe follows the simple law: $\langle i^2 \rangle = C I_{DC}^{\alpha} f^{-\beta}$ over several decades in frequency below 10kHz, with $\alpha \approx 2.0$ and $\beta \approx 0.9$. The constant C was found to depend inversely on sample volume; $C = C_2/V$ and $C_2 \approx 2.4 \times 10^{-20}$ [$cm^3 Hz^{\beta-1}$].

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In the presence of strong contact noise the bias current dependence of $\langle i^2 \rangle$ becomes more complicated than I_{DC}^{α}. Effects of ambients on 1/f noise are discussed.

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1/f Noise in Amorphous GeTe

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J. R. Dixon

J. R. DIXON
By direction

I. INTRODUCTION

At frequencies below one hundred Hz and at almost all practical applied voltages, the major source of noise in thin amorphous GeTe films of submillimeter planar dimensions is current noise. Its spectral power density may be expressed in the form:

$$\text{(1)} \qquad \langle i^2 \rangle \left(\frac{A^2}{Hz}\right) = C I_{DC}^{\alpha} f^{-\beta}$$

where α and β are positive constants. I_{DC} is the bias current, f the frequency and C is a characteristic constant for a given sample geometry. If we assume an uncorrelated volume distribution of current noise sources, then simple dimensional arguments lead us to conclude that $C = C_2/V$, where V is the sample volume and C_2 is a material constant. If $\alpha = 2$ and $\beta = 1$, then C_2 is a volume.

The current noise voltage of a sample in unit bandwidth across a load resistor R_L at 10 Hz is typically at least ten times larger than thermal noise. Consider a representative example. Let $C \simeq 2.0 \times 10^{-12}$, $I_{DC} = 2 \times 10^{-6}$ A and $R_L = 2.6 \times 10^{6}\Omega$. Then at room temperature the ratio of current and thermal noise powers at the amplifier input terminals is:

$$\frac{\overline{V^2_{cn}}}{\overline{V^2_{jn}}} = \frac{C I_{DC}^2 R_L}{4KTf} = 1.3 \times 10^2, \text{ with } KT = 2.6 \times 10^{-2}\text{eV}.$$

Here we have set $\alpha = 2$, which is approximately correct, as will be shown in section 3. A current level of 2μA can be achieved with a bias voltage of 300 volts and sample length (ℓ), width (w), and thickness (d), of 250μ x 250μ x 2000 Å respectively, hence with a sample volume of $1.25 \times 10^{-8}\text{cm}^3$ and a resistance of $1.5 \times 10^{8}\Omega$.

Current noise has been found in a large variety of substances and systems. The essential feature of a power spectrum proportional to $f^{-\beta}$, where β is a constant near unity over a number of decades of frequency, has been observed in "carbon

granules, carbon filaments, graphite powder, pyrolytic carbon films, germanium filaments, thin metal films, lead sulphide films, all kinds of rectifying barriers in germanium, silicon and metallic oxides, single crystal cuprous oxide, the interface layer between cathode sleeve and coating in an oxide-coated valve, and the thermionic emission from oxide coated valves (flicker effect)." [1] To this we can add, e.g. amorphous semiconductors, surface channels in MOS transistors, and the list goes on. Amorphous semiconductors are of course of special interest to us. In section 3 we will compare our own results with some data on Ge_xH_{1-x} [2] and on glasses of the As-Tl-Te-Se family. [3]

The presence of current noise in amorphous GeTe is therefore not in the least surprising. It is the magnitude of this noise that is at issue here. Because of the overriding importance of current noise in micro-films of amorphous GeTe and because these films are presently considered as potentially useful photoconductive detectors, we decided to study it carefully and find out if this type of noise was mostly contact related, therefore potentially removable, or if most of it or all of it originated in the bulk of the material itself and hence was there to stay. This question, as well as questions relating to the magnitude and structure of the constant C in Eq. (1) are the main topics of discussion in the present report. We are not concerned with philosophical issues relating to the nature of current noise. In particular, whether or not the 1/f - law might extend to very low frequencies, does not concern us here. We are primarily interested in the frequency range between several Hz and several hundred Hz.

The salient features of our results to date can be summarized as follows:
1) The exponent β in $\langle i^2 \rangle$ is always found to be of order unity over a range of frequencies between 2 and 2×10^4 Hz.
2) Samples with the least amount of current noise also exhibit the most accurate quadratic dependence of $\langle i^2 \rangle$ on I_{DC}. If the general noise level is high in a given sample, then the drive current dependence of $\langle i^2 \rangle$ is more complicated than I_{DC}^{α}.

---

[1] Electrical Noise, D. A. Bell (D. Van Norstrand Co. Ltd., 1960).

[2] T. D. Moustakas and G. A. N. Connell, J. of Appl. Phys., 47, 1322 (1976).

[3] C. Main and A. E. Owen, Phys. Stat. Sol., (a 1), 297 (1970).

The evidence suggests that the high noise samples contain substantial noise sources which are localized near the electrodes; relatively low noise samples do not. It appears therefore that low noise samples which exhibit almost a perfect $[I_{DC}^2/f]$ - dependence of current noise power spectral density on current and frequency are bulk limited 1/f-noise generators. From these latter samples we can derive a value for the material constant C_2 of amorphous GeTe. Our data to date indicate that this value is about 2×10^{-20} $(cm^3 Hz^{\beta-1})$. The simple expression, $C = C_2/V$ holds well over a certain range of sample lengths.

The absolute minimum noise power to be expected from amorphous GeTe films of any dimensions of practical interest can therefore be calculated from Eq. (1), with C_2, α and β as determined in this work. Minor restrictions on the applicability of our results may arise from the theoretical requirement that the current distribution in the material be uniform. The distribution is reasonably uniform however in all configurations in which the length to thickness ratio of the film is much larger than unity, as will be the case in most films of practical importance.

II. EXPERIMENTAL PROCEDURE

Careful current noise measurements on a number of samples with different electrodes (gold, chromium and molybdenum) indicated that low current noise spectra were of the simple form shown in Eq. (1), with $\alpha \simeq 2$ and $\beta \simeq .93$. We found however that both α and β changed with time and it also became clear that these low noise spectra were the exception rather than the rule. Usually current noise was high; values of C_2 derived from Eq. (1) were of order 10^{-19} $cm^3 Hz^{\beta-1}$. The films were often exposed to ambients for several days before electrodes were deposited. Electrode depositions took place in marginal vacua; of the order of 10^{-4} torr and measurements were carried out at pressures of the order of 10^{-3} torr. No protective coatings were applied to exposed surfaces.

Although similar results had been obtained for three different electrode materials, the possibility remained that the contact areas near the electrodes were contributing to the noise, thus masking the bulk current noise level of amorphous GeTe itself. In addition, a way of making low noise samples consistently had to be found. To this end we designed an experiment which would address both problems simultaneously.

Because of the comparatively high resistivity of this material, $\rho = 3 \times 10^3 \Omega$cm at 300°K and because of our small sample dimensions, which lead to sample resistances of the order of 100MΩ in many cases, it was impractical to try to eliminate electrode contributions to the noise by using e.g. a constant current source and a four probe measuring technique. We therefore decided to try to detect contact noise as a more or less constant contribution to a variable amount of background noise. This was done by sequentially evaporating overlapping gold electrodes along a length of amorphous GeTe film and measuring the noise of the resulting sequence of samples of decreasing lengths. This method is perhaps more instructive and more straightforward than one based on a sample design which leads to lower current densities in the electrodes than in the sample proper. The gold electrodes in our experiment were deposited in relatively good vacuum of the order of 10^{-6} torr and we believe it is possible to make them with fairly reproducible current noise powers on any given film. The kind of multiple masking which would have allowed us to make the amorphous film and the electrodes in situ was not available to us and a compromise in sample preparation procedure had to be used. Six millimeter long sections of amorphous GeTe of different thicknesses and widths were deposited on 10 to 20 mil

thick Corning 0211 glass substrates by means of thermal evaporation from a nominally stochiometric source. The resulting film was then removed from the vacuum system and gold electrodes were evaporated across both ends in a second evaporator. The glass substrate was bonded to an aluminum heat sink by means of silver paint and mounted in a gold evaporator which was equipped with a movable mask. Displacement of the mask was accurate to within 25 microns. Electrical contact between fixed leads in the evaporator and each sample was established via #48 copper wires which were soldered at the evaporator end and silver painted to the gold contacts at the sample end.

Before the start of the experiment the sample remained in a vacuum of about 10^{-6} torr for at least 10 hours. The purpose of this delay was to establish stable sample conditions since we found that large reversible changes of resistance occurred when the samples were exposed to ambients. After this delay a new set of gold electrodes was made in situ by overlapping the existing electrodes at both ends. It was felt that shorting out the old electrodes in high vacuum would probably lead to more reproducible results in view of the potential influence of ambients on contact noise. A series of samples of decreasing lengths was then generated by repeatedly depositing overlapping electrodes.

For each sample length noise measurements were made at a number of different bias current levels and at four different frequencies; 5, 10, 20 and 30 Hz. From the measurements it is possible to obtain the frequency and bias current dependence of the current noise and one can calculate the constant C in Eq. (1) for each sample length. This constant can be expressed in terms of C_1, an assumed contact current noise constant for a particular film and C_2, the current noise constant of amorphous GeTe. The simplest expression of this type is:

$$C = \left\{ \frac{R_1^2 C_1 + \left(\frac{\rho \ell}{A}\right)^2 \left(\frac{C_2}{A\ell}\right)}{\left[R_1 + \left(\frac{\rho \ell}{A}\right)\right]^2} \right\}, \qquad (2)$$

where:

R_1 is the total contact resistance between gold and amorphous GeTe and A is the crossectional area of the sample. The formula is based on the assumption that the 1/f - dependence of both contact and bulk noise is roughly the same and that both types of noise powers are proportional to I_{DC}^{α}, α being the same for both. We have also assumed that the bulk noise sources are spatially independent. Eq. (2) then

follows in a straightforward manner from simple arguments based on electric circuit theory.[4] There may be objections to the implicit assumption that C_2 is independent of film thickness. We are attempting to analyze the data as if current noise were strictly a bulk noise phenomenon, with little or no contributions from surface channel fluctuations. The assumption is probably a fairly good one however since trap densities in the bandgap throughout the bulk of the material are high, unlike the situation in crystalline semiconductors, and the Fermi level is substantially pinned all the way out to the surface. Thus there is little freedom for surface channel fluctuations in what is known to be a narrow (<100 Å wide [5]) channel in any case. On the other hand we have seen some effects of ambients, as will be described below. The value of C_2 derived from films of significantly different thicknesses, assuming that C_2 was not a function of thickness, are in substantial agreement however.

The denominator in the above formula is of course just the square of the total sample resistance, R_T, and hence plotting CR_T^2 as a function of ℓ should yield a straight line. The intercept, $C_1R_1^2$, will be a measure of the contact noise and the slope will yield C_2, since ρ, ℓ and A are known from independent measurements. Any decision as to the presence or absence of contact noise should not depend in first approximation on the assumption that both bulk and contact noise have the same 1/f - dependence, or even the same I_{DC} - dependence, since we can always analyze the data at a given frequency and drive current, for varying sample lengths. But it does depend on the assumption of spatial independence of all noise sources and on the assumption of a uniformly distributed current since these latter assumptions can effect the ℓ-dependence of C. Our experiments suggest that at least over a limited range of lengths depending perhaps on the sample width, the simple linear dependence of CR_T^2 on ℓ holds well. If the contact noise problem is severe, then it seems as though the contacts may be modifying the drive current dependence of the bulk current noise. In that case $\langle i^2 \rangle$ and C cannot be written as in Eq. (1) and (2). We will return to this discussion after presenting the data.

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[4] The basic elements of this argument may be found in: Elements of Infrared Technology, Generation, Transmission and Detection, P. W. Kruse, L. D. McGlauchlin, R. B. McQuistan (John Wiley & Sons Inc., N. Y., 1962).

[5] D. F. Barbe, J. of Vac. Sci. and Technology, 8, 102 (1970).

The PAR 117 Preamplifier and the PAR 124 Lock-in were used for these measurements. The 10% NEBW mode of the PAR 124 was found to be adequate for our purposes. We have compared the 10% NEBW results with those obtained from a higher Q mode (Q=100) and found them to be identical. The high Q mode was calibrated against thermal noise. Before each noise measurement at a new drive current setting, the thermal noise level was checked at all operating frequencies, to make sure that this theoretical base level was actually present during each measurement. Current noise and Johnson noise were the major noise sources at any drive current. The absence of shot noise was confirmed by looking in a frequency range between the corner frequency of current noise and the RC-cutoff of the circuit. No substantial noise component was detected that could not be accounted for by current noise and Johnson noise alone. The absence of battery noise, as well as noise from all other parts of the circuit, especially from the silver paint contacts, was checked carefully by simply inserting a 2.5MΩ wirewound resistor in place of the sample while keeping the gold film leads and the silver paint contacts in the circuit. With this arrangement we measured only thermal noise up to bias current levels several times higher than those used during the experiments. The load resistor was a 2.5MΩ wirewound inside a mumetal shield. Electromagnetic pickup was eliminated by carefully shielding the entire circuit and the vacuum pumps and by grounding only at the input of the PAR 117. Pickup from mechanical vibrations was eliminated by means of mechanical damping, especially at the major source, the forepump and by carefully tying down all electrical leads. The temperature of the sample was obtained from the temperature of the substrate holder. All sample resistances were adjusted to their value at an arbitrarily chosen standard temperature, T_0 = 74°F (296.4°K), using the expression $R_T \equiv R(74°F) = R(Exp) \exp\left[\frac{\Delta E}{K}\left(\frac{1}{T_0} - \frac{1}{T}\right)\right]$ where R (Exp) is the measured sample resistance, T is the Kelvin temperature, K is the Boltzmann constant and ΔE = 0.4eV, a value which was found to apply to our samples as a rule,[6,7] but was not verified in each case. The error in ΔE is expected to be less than ±0.02eV. Temperature excursions during any given run were <±3°K above and below the standard temperature. Hence the maximum error in our calculation of the standard resistance is expected to be less than ±0.8%. Applied electric fields were less than 10^4 V/cm.

[6] K. P. Scharnhorst, H. R. Riedl, NOLTR 72-196.

[7] K. P. Scharnhorst and H. R. Riedl, J. of Appl. Phys., 45, 2971 (1974).

Resistances were linear in this range of fields. Sample lengths were measured with a travelling microscope. Sample thicknesses were obtained from a Varian Model 980-4000 Angstrometer.

III. RESULTS AND DISCUSSION

1. Bulk Current Noise.

We first consider data which can be interpreted most simply by choosing $\alpha \simeq 2.0$ and $\beta \simeq 0.93$ at frequencies between 5 and 30 Hz; the data of samples #1 through 7, Table 1. These were referred to as "low noise" samples. Samples #4, 5 and 6 were used to check the drive current dependence of the noise power spectral density at 10 Hz and its frequency dependence at fixed drive current over an extended range of frequencies, Figures 1, 2. The sample length dependence of current noise was not studied in these latter samples and it should also be noted that experiments with samples #4, 5 and 6 were not carried out in situ. The dimensions of these three samples were all very similar and we expected to obtain practically identical results, provided of course that contact noise from the three different electrodes was either absent or was roughly the same for all. The low values for C_2 derived from this data, as well as the almost perfect quadratic drive current dependence of the current noise power suggested that little contact noise was present. Yet the results were not identical and data taken at different times did not agree exactly. This effect is mostly due, we believe, to the influence of ambients, a topic which will be discussed below. In view of the fact that these samples were not studied in situ it is surprising that the results are fairly consistent nevertheless.

The measurements show that the noise power can be fitted to the simple expression of Eq. (1) with $\alpha \simeq 2$ and $\beta = 0.90$ to 0.94 over a limited frequency range. At low frequencies, $f < 10$Hz, we sometimes observe $\beta < 0.90$; at high frequencies, $f > 10$ kHz, $\beta > 1.0$. At frequencies in the 10 kHz range the data becomes increasingly inaccurate since current noise power, which is the difference between the total measured noise power and Johnson noise was comparable in magnitude with Johnson noise at these frequencies. It should also be noted that the deviation of β from unity implies a weak dimensional dependence of C and hence of C_2 on frequency. This is not shown explicitly in the figures. The dimension of C_2 is simply written as a volume; it should be understood to be $cm^3 Hz^{\beta-1}$, where $(1-\beta)$ has been observed to lie between 0.06 and 0.10, the exact value depending on sample history and ambients in some as yet poorly understood way.

Both β and α are suggestively close to their ideal values, 1.0 and 2.0 respectively in the perfect 1/f-law, Eq. (1) and these measurements will have to be

repeated in situ in order to clarify any possible influence which residual contact noise and/or ambients may have had on the values of α and β.

Next we turn to in situ studies of the sample length dependence of current noise power. We want to examine the quantity CR_T^2, which is directly related to measured quantities, namely the voltage noise spectra. We will call this quantity the "normalized voltage noise power" (of current noise) since it is obtained from $V^2 = i^2R_T^2$ by multiplying with $I_{DC}^{-\alpha} f^{\beta}$. Later on we also consider the quantity $C_2\rho^2$, which is related to CR_T^2 as in Eq. (2). Because of this connection between the two quantities and also because both C_2 and ρ are material constants, the quantity $C_2\rho^2$ will be called the "specific voltage noise power".

Values of CR_T^2 for lengths ranging from 110 microns to ≃ 1.5 mm and for two different widths, 1.27 mm and 300 microns are shown in Figure 3. Evidently the linear dependence of CR_T^2 on ℓ, which is predicted by Eq. (2) holds fairly well. Sample #2 shows practically no intercept at all, indicating negligible contact noise. Samples #1 and 3 show relatively small intercepts, indicating some contact noise. The data for these three samples were obtained by averaging a number of values for C derived from measurements at several different current levels and at two different frequencies; 5 and 10 Hz, with $\beta = 0.9$. The current noise power of sample #3 was only proportional to I_{DC}^2 at currents > 1.5μA. We will return to this problem below.

Because of the different sample thicknesses and widths we would expect, and we find, a considerable spread in the slope of the straight lines in Figure 3. According to Eq.(2) the slope should be equal to $C_2\rho^2/A^3$ where the specific voltage noise power, $C_2\rho^2$, is expected to be constant; the slope varies as $1/A^3$. The value of $C_2\rho^2$ is shown in Figure 4. Evidently there is some uncertainty with respect to the exact value, but not by more than a factor of two. We believe that this is within our experimental error, particularly in view of the fact that A^3 of samples #1 and 2 differ by a large factor, a factor of 60. Note also that we are showing results for a larger range of lengths for sample #1 than are given in Figure 3. The longer samples will be discussed in subsection 4.

A comparison of the data for ρ and C_2 in Figures 5 and 6 shows that most of the uncertainty in the value of the specific voltage noise power is due to C_2. But again the values of C_2 differ by only a factor of two. It appears therefore that our procedure of subtracting the intercept of CR_T^2 versus ℓ at $\ell = 0$ and calculating

C_2 from the remainder at each ℓ works well, at least for relatively low noise samples. If we had not subtracted the intercept at $\ell = 110$ microns of sample #3 for instance the value of C_2 would have been 5.1×10^{-20} cm^3 rather than 1.84×10^{-20} cm^3 as shown in Figure 6. Similarly the slope of C_2 (ℓ) of sample #1 would have been much steeper without the intercept-correction. We will return to the question concerning the slope for this sample in subsection 4.

The average value of C_2 in Figure 6 is $2.35 \times 10^{-20} cm^3 Hz^{\beta-1}$. Suppose we neglect the weak dimensional dependence of C_2 on frequency. Since we are dealing with an isotropic material, it seems reasonable to think of C_2 in terms of a cube or a sphere. The edge of such a cube would be $(2.35 \times 10^{-20})^{1/3} \approx 30$ Å. The derivation of Eq. (2) implies that C_2 is a measure of the volume occupied by the basic, independently fluctuating current noise source in the bulk of the material. What determines this volume? It has been suggested that C_2 is related to the volume per free carrier. By fitting Eq. (1) to a large amount of current noise data in diverse systems, $C_2 \approx 2 \times 10^{-3}/n$ was obtained, [8,9] where n is the free carrier density. Hence $n \approx 10^{17}/cm^3$ for amorphous GeTe at room temperature. Using this value in the D.C. conductivity $\sigma = ne\bar{\mu} = 3 \times 10^{-4} (\Omega cm)^{-1}$, we find $\bar{\mu} = 2 \times 10^{-2} \frac{cm^2}{V\,sec}$ for the free carrier mobility at the mobility edge. A value of 1 to 10 would have been more acceptable for amorphous GeTe.[10] Nevertheless we believe that the hypothesis, $C_2 \propto 1/n$, should be pursued. A first step would be to look at the temperature dependence of C_2. In the present work C_2 was assumed to be independent of temperature.

2. Effects of Ambients: Weak Contact Noise.

The values of C_2 for sample #2 are rather high in spite of the fact that the intercept of CR_T^2 seems to be accurately equal to zero. We believe the answer to this seemingly exceptional behavior will eventually be found in the way in which these samples age. The three points marked sample #2 actually belong to the same film as those marked sample #7. The difference is that the vacuum system was opened up for about one hour after the fifth run at $\ell = 0.82$ mm and the sample exposed to ambient. Subsequently the vacuum was held near 10^{-6} torr again for 24 hours and measurements were resumed. As Figure 6 shows, the noise power had clearly

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[8] F. N. Hooge, Phys. Letters, A29, 139 (1969).

[9] L. K. J. Vandamme, Phys. Letters, A49, 233 (1974).

[10] K. P. Scharnhorst and H. R. Riedl, J. of Appl Phys., 43, 5142 (1972).

increased by about a factor of 1.5 after this procedure. Interestingly enough, the resistivity of the sample did not change however, Figure 5. The fact that the data for the normalized voltage noise power can be extrapolated to zero at $\ell = 0$ suggests that whatever the effect, it was not localized near the electrodes. This was a thin sample, $d = 1.9 \times 10^{-5}$ cm, and hence surface effects and/or effects due to in-diffusion of ambients would have shown up strongly. Slight increases of noise with time at high vacuum of the order of 10^{-6} torr without changes in resistivity have also been observed in thicker samples.

The effects of ambients and of surface conditions in general clearly need further investigation. Our priliminary studies have shown that the resistance of thin films of amorphous GeTe without protective coating is extremely sensitive to exposure to ambients. Figure 7 shows the response of the resistance of 3600 Å thick films to sudden exposure to dry air. These samples were mounted side by side. One surface was exposed, the other one was covered with about 1000 Å of sputtered SiO_x. The resistances and the temperature of the common glass substrate (Corning 0211) were measured simultaneously and all resistances were reduced to their value at the standard temperature of 294.0°K using the procedure indicated in section II. The covered film hardly responded at all, whereas the uncovered film shows an enormous sensitivity to this change in environment and it did not completely recover its original resistance upon subsequent storage at 5×10^{-6} torr. Note also the persistent slow downward drift of the resistance of both samples, amounting to 2% in about four days, in spite of the fact that the samples had been kept at a pressure of 5×10^{-6} torr for more than 10 days before this data was taken.

Our results to date indicate that resistance changes incurred under short exposures to ambients are reversible to within a few percent whereas the effects of ambients on the noise power, which are equally as strong, are not. These latter effects are therefore extremely important with respect to performance figures of devices, such as the NEP of photoconductive detectors. A protective overlay will eventually have to be devised for films in practical devices. We have some indications that overlays of SiO_x help to stabilize the resistance over long periods of time; of the order of one year, but we do not know at present how this type of overlay effects the current noise.

3. **Effects of Ambients: Moderate and Strong Contact Noise.**

Problems with ambients are probably also reflected in the results for sample #8. The values of C_2 and $C_2\rho^2$ are considerably above those of the other samples, Figures 4, and 6. This sample was not measured in situ. It was exposed to ambients for every electrode deposition and the vacuum during the measurements was of order 10^{-3} torr. The noise data are based on measurements at 1μA drive current only and are averages for f = 5 and 10 Hz. The drive current dependence of the current noise power deviated strongly from the simple law of Eq. (1). A large intercept on the CR_T^2 versus ℓ plot indicates very strong contact noise and subtracting this intercept from CR_T^2 did not give us the usual bulk value for C_2, Figure 6.

It is not difficult to advance at least some qualitative arguments which will explain this type of result. If the current enters and leaves the sample at isolated points along the edges of the electrodes for instance, then not only do we expect much enhanced current noise from the contacts but we also have to expect increased current noise from the sample proper, since the current distribution in it is not uniform under these circumstances. Some parts of the sample near the electrodes carry practically no current at all. In these regions the cross section of the sample is effectively reduced and the total noise voltage power of the sample proper, which is just the sum of contributions from regions carrying uniform current and regions carrying non-uniform current, must increase, essentially as a consequence of the A^{-3} - dependence of CR_T^2 in Eq. (2). Furthermore as the voltage across the sample is increased, it is conceivable that the number of points across which current enters and leaves also increases. The current distribution in the sample will then become more uniform and we should expect the bulk noise power contribution to approach the I_{DC}^2 - dependence.

In case of strong electrode noise, as indicated by a value of C_2 based on Eq. (2) which is much larger than the bulk value, a better approximation to our measured noise power would be an expression of the form:

$$(3) \qquad CR_T^2 f(I_{DC},\ell) = C_1 R_1^2 g(I_{DC},\ell) + \left(\frac{\rho\ell}{A}\right)^2 \left(\frac{C_2}{A\ell}\right) h\,(I_{DC},\ell)$$

where the functions f, g and h are unknown. The dependence of g on ℓ is random, whereas that of f and h on ℓ is partly random through g, but should otherwise be determined by the length (and width) of the sample. We are assuming again that the frequency dependence of current noise for both bulk and contacts is roughly the

same. Evidently there is little hope for, or interest in analyzing this formula.

As contact noise decreases however the first term on the right becomes negligibly small; $f(I_{DC},\ell)$, $h(I_{DC},\ell) \rightarrow \approx I_{DC}^2$ and Eq. (2) is recovered. Correspondingly the results of sample #8 can be understood on the basis of a somewhat simpler expression than Eq. (3) namely:

$$(4) \qquad CR_T^2\, f(I_{DC}) = C_1 R_1^2\, g(I_{DC}) + \left(\frac{\rho\ell}{A}\right)^2 \left(\frac{C_2}{A\ell}\right) I_{DC}^{\alpha}$$

We are assuming that the electrodes, although noisy, inject a quasi-uniform current distribution and the only dependence on ℓ enters via the coefficient of I_{DC}^{α}. If we assume $\alpha = 2$, we obtain the results shown in Figures 4 and 6 (using $I_{DC} = 1\mu A$). Had we assumed e.g. $\alpha = 1.83$ then C_2 would have been about one order of magnitude smaller; we would have recovered the bulk value of C_2 as given by samples #1 through 7. A deviation from $\alpha = 2$ might be a reflection of some influence of non-uniformly injecting electrodes on the current distribution in parts of the sample.

In view of these theoretical complications it is best not to try to deduce the value of C_2 from samples showing strong contact noise. The approximate constancy of the value of this parameter in the case of sample #8 at four different sample lengths should be regarded as fortuitous.

In the presence of a moderate amount of electrode noise bulk noise will dominate and the I_{DC}^2-law should be obtained. We have in fact observed this behavior in sample #3. The data for sample #3 are averages for drive currents in excess of 1.5μA, for which the drive current dependence of the current noise power was quadratic. Note also that this sample has the largest CR_T^2-intercept of those measured in situ. It is not clear at the present time why it showed as much contact noise as it did, in spite of the fact that it was measured in high vacuum. We have however had a slight problem with the reproducibility of the (light-) microscopically observable structure of our amorphous films, in particular with their surface structure. This would obviously be expected to have an influence on both contact noise and bulk noise. The thicker films occasionally grow with irregular surfaces. As a result of these observations we are paying more attention now to the microstructure and have initiated an effort to improve our sample preparation procedure. Exposure of samples to ambient during transfer from one evaporator to the other is also a potential source of trouble of course. But this is evidently not a major difficulty as indicated by the results for samples #1 and 2.

4. The Normalized Voltage Noise Power Versus Sample Length.

The data for our wide, low noise samples, #1 and 7, indicate that when $\ell > w$, $CR_T^2(\ell)$ becomes sublinear, Figures 8 and 9. The case is most convincing for sample #1. If we replot CR_T^2 for this sample, using the average value of ρ for all lengths of the series, the result shown in Figure 8 is obtained. This is probably the more correct way to proceed in this case since there seems to be a slight systematic error in the measured resistivities of the short samples, Figure 5. There is a larger intercept now, which when taken into account, leads to the corrected values for C_2 as shown in Figure 10. Most importantly however, the sublinear behavior of CR_T^2 for the long samples in this series is still present in the corrected data. This will be of interest in connection with the theoretical interpretation of bulk current noise in amorphous GeTe films of different dimensions. Film #3 for instance, where w = 0.3 mm and all but the shortest sample in the series had a length to width ratio larger than unity did not show this sublinear dependence of CR_T^2 on ℓ at $\ell > w$, Figure 3. It is conceivable that a correlation length exists for current noise fluctuations which effectively introduces the absolute value of w into the expression for $\langle i^2 \rangle$ The quantity $(C_2)^{1/3}$ would be such a length, although it seems to be much too small to manifest itself on the scale of sample dimensions considered here.

The case for sample #7 is not as convincing since for lengths shorter than 0.82 mm, no data are available. The slope of the straight line in Figure 9 is based on the assumption that the intercept of $CR_T^2(\ell)$ is zero. Also there seems to be a slight error in both ρ and C_2 at ℓ = 2.48 mm as indicated by the trend of the data in Figures 5 and 6. Using the average resistivity in this case, puts all points in $CR_T^2(\ell)$, except $CR_T^2(\ell = 2.48$ mm) on two straight lines through the origin (data for samples #2 and 7). Note however that corrections required for sample #7 are much smaller than those required for sample #1 since the range of lengths is much smaller in the former. Clearly these measurements should be repeated to establish the ℓ-dependence of C_2 for large ℓ.

5. Comparison with Current Noise in Other Amorphous Semiconductors.

In the two As-glass systems, $As_2Te_3Tl_2Se$ and As_2TeSe_2, α was found to be less than two and somewhat dependent on electrode material.[3] The parameter β was found to be larger than unity in the frequency range between 100 Hz and a few tens of kHz.

The authors[9] speculate that the deviation from $\alpha = 2$ may have been due to a non-uniform current distribution and conclude that (with respect to the high resistivity glass As_2TeSe_2) "it remains to be determined to what extent the noise is a property of surface or contact effects:"[3] This is precisely one of the questions we have addressed in the present work and the evidence at this point in time strongly suggests that in the case of amorphous GeTe such deviations from $\alpha = 2$ and $\beta = 1$ are in fact largely if not exclusively due to contact effects.

The values of C($As_2Te_3Tl_2Se$, InGa electrodes) and C(As_2TeSe_2,InGa electrodes) were found to be 2.04×10^{-15} and 1.1×10^{-13} respectively. These values of course imply rather different current noise powers for the samples studied. But if we take the sample volumes into consideration, as quoted in the original work and calculate C_2, which is more closely related to a "specific current noise power", we find that $C_2(As_2Te_3Tl_2Se)/C_2(As_2TeSe_2) = 3.2 \times 10^{-16}/8.3 \times 10^{-17} = 3.9$. Hence the specific noise powers are not very different and the low resistivity glass, $As_2Te_3Tl_2Se$; $\rho = 3 \times 10^3\,\Omega$cm(the same as ρ(GeTe)) is in fact noisier than the high resistivity glass As_2TeSe_2; $\rho = 3 \times 10^5\,\Omega$cm. Since there may have been some contact noise in these samples, this simple procedure of arriving at C_2 is at best precarious. If we go ahead nevertheless and assume that contact noise in the As-glasses was not of overriding importance, we arrive at the further conclusion that both As-glasses are about 10^3 to 10^4 times noisier than amorphous GeTe. However in view of the essential similarities of the D.C. conduction mechanisms in all of these amorphous chalcogenide systems,[11] e.g. conduction by carriers in extended states, it is difficult to believe that their current noise spectra should be so different. We therefore take the opposite point of view and suggest that a considerable amount of contact noise was indeed present in both As-glass samples. Accordingly it seems that the potentially attainable noise level, the "bulk noise" level, in these glasses might be significantly lower than has been measured so far.

Another example of current noise in an amorphous system which is more closely related to a GeTe has recently appeared in the literature in connection with the evaluation of rf-sputtered a-$Ge_{1-x}H_x$ bolometers. The authors state that 1/f noise in their devices was probably generated at the contacts. Nichrome electrodes were used. A $1/f^{1.0}$ - dependence of $\langle i^2 \rangle$ was reported, but the drive current dependence

[11] Electronic Processes in Non-Crystalline Materials, N. F. Mott and E. A. Davis (Clarendon Press, Oxford, 1971).

was not given. If we go ahead anyway and calculate C_2 from their data, assuming that contact noise was negligible and that $\langle i^2\rangle \propto I_{DC}^2$, we find: $C_2[Ge_{0.96}H_{0.04}] = 7.6 \times 10^{-21}$ cm^3, which is indeed close to what we measured for GeTe. The dimensions of their sample were: d = 25μ (which is very different from any thickness considered in the present work), ℓ = 100μ and w = 1.6 mm. Their sample resistance was $4.2 \times 10^5 \Omega$ at 300°K (=>ρ(300°K) = $1.7 \times 10^3 \Omega$cm) and the drive current was 20μA.

IV. CONCLUSIONS

It appears that our approach to the problem of determining the current noise power of amorphous GeTe is feasible. The results indicate that the current noise power follows the simple law $\langle i^2\rangle = CI_{DC}^{\alpha}/f^{\beta}$ where $\alpha \simeq 2.0$ and $\beta = 0.90 - 0.94$ over several decades in frequency below f = 10 kHz. Whenever strong deviations from the I_{DC}^2 - dependence of the current noise power spectral density are observed, a considerable amount of contact noise is invariably present. Our results show that it is possible to eliminate contact noise by means of in situ sample processing techniques.

The proportionality constant C in $\langle i^2\rangle$ depends inversely on the volume of the sample over a limited range of sample lengths. The average value of C_2 indicated by the present work is $2.4 \times 10^{-20} cm^3 Hz^{\beta-1}$. Before we can obtain a more definitive value for this parameter, it is necessary to understand the effects of ambients and of sample surface conditions on the noise power density. It may also be possible to improve the bulk-structure of our samples to some extent. Hence it is very likely that the final value of C_2 will be somewhat smaller than that given here. For practical applications the effect of an overlay on C_2 also has to be understood.

Much information about the physical properties of amorphous semiconductors has been gathered in recent years. Only very few attempts have been made however to analyze the current noise power spectral density, presumably because of difficulties encountered in dealing with contact noise. The present experimental approach to this problem seems to be particularly well suited for films of amorphous semiconductors and should be pursued in materials of this kind. Similarities and differences in electronic structures will almost certainly be reflected in the values of C_2.

V. ACKNOWLEDGEMENTS

It is a pleasure to acknowledge the help of Mr. G. Black and Mr. D. Demske in setting up the experimental apparatus, making the samples and carrying out some of the measurements.

FIGURE CAPTIONS

1. Current noise power spectral density as a function of the applied current at f = 10 Hz;

   □ — Chromium electrodes, Sample #5

   ◇ — Gold electrodes, Sample #4

   ○ — Molybdenum electrodes, Sample #6

2. The current noise power spectral density as a function of frequency;

   □ — Chromium electrodes, I_{DC} = 1.6μA.

   ◇ — Gold electrodes, I_{DC} = 4.0μA.

   ○ — Molybdenum electrodes, I_{DC} = 1.9μA.

3. The normalized voltage noise power, CR_T^2 versus sample length for samples

   #1 - ▽ , left hand scale

   #2 - ○ , right hand scale

   #3 - □ , right hand scale

   #8 - △ , right hand scale and insert

4. The specific voltage noise power, $C_2\rho^2$(296.4°K) versus sample length for samples #1 - ▽ , #2 - ○ , #3 - □ , #7 - ◊ , #8 - △ .

5. The resistivity versus sample length for samples #1 - ▽ , #2 - ○ , #3 - □ , #7 - ◊ , #8 - △ .

6. The current noise power constant, C_2, versus sample length for samples #1 - ▽ , #2 - ○ , #3 - □ , #4 - ◇ , #5 - ◯ , #6 - ◯ , #7 - ◊ , #8 - △ .

7. The percentage change of R_T(294°K), ΔR_T, of amorphous GeTe films relative to R_T after the 10th day of storage in a vacuum of 5 x 10^{-6} torr. □ - 3600Å thick, coated with 1000 Å of sputtered SiO_x. ○ - 3600 Å thick, not coated. At t = t_b the system was pressurized with one atmosphere of dry air. Subsequent pumpdown started at t = t_C. The pressure of 5 x 10^{-6} torr was recovered in about one hour. The time at atmospheric pressure was $\Delta t = (t_C - t_b) \simeq$ 5 hours.

8. The normalized voltage noise power, CR_T^2 versus sample length of sample #1; ▽ - based on ρ(296.4°K) as calculated from measurements at each ℓ, ○ - based on the average $\bar{\rho}$ (296.4°K) obtained from the complete sequence of lengths of sample #1.

9. The normalized voltage noise power, CR_T^2 versus sample length of samples #2 and 7. All points are based on the values of $\rho(296.4°K)$ which were calculated directly from measurements at each particular ℓ. ◯ - sample #2, ◊ - sample #7.

10. The current noise power constant, C_2 of sample #1 as a function of sample length; ∇ - based on $\rho(296.4°K)$ as calculated from measurements at each ℓ, ◯ - based on the average $\overline{\rho}$ (296.4°K) obtained from the complete sequence of lengths of sample #1.

TABLE CAPTIONS

1. A list of the amorphous GeTe samples discussed in the present work.

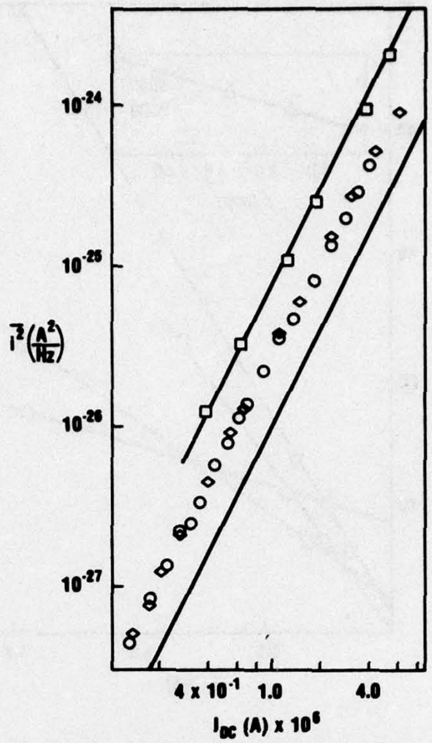

FIG. 1 THE CURRENT NOISE POWER SPECTRAL DENSITY AT f=10 Hz AS A FUNCTION OF APPLIED CURRENT

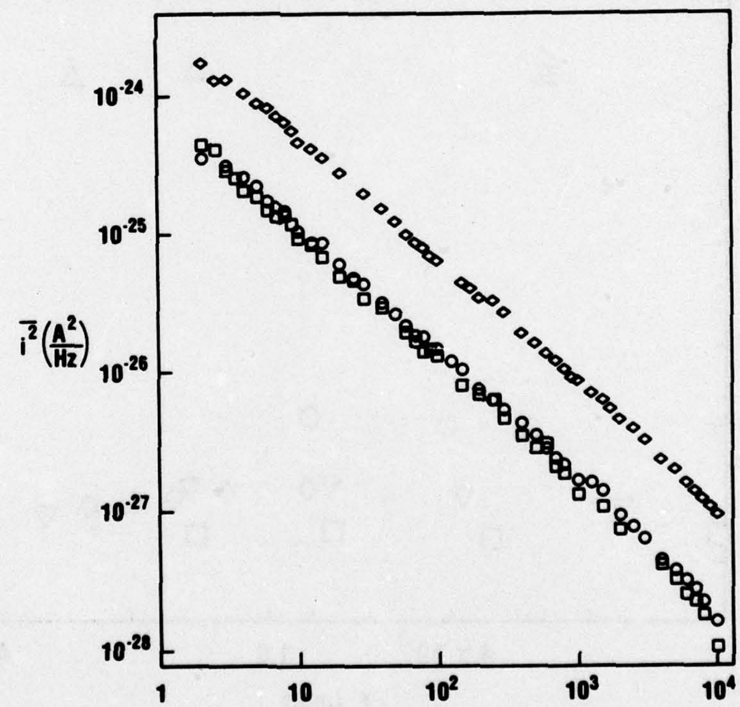

FIG. 2 THE CURRENT NOISE POWER SPECTRAL DENSITY AS A FUNCTION OF FREQUENCY

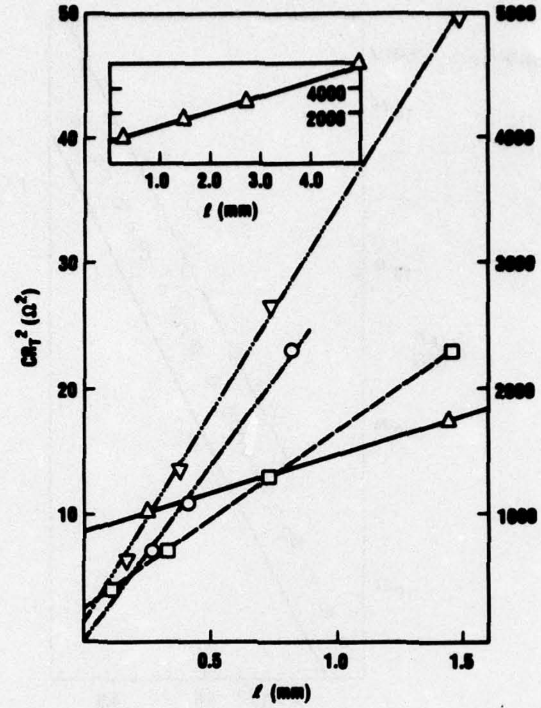

FIG. 3 VOLTAGE NOISE POWER AS A FUNCTION OF SAMPLE LENGTH

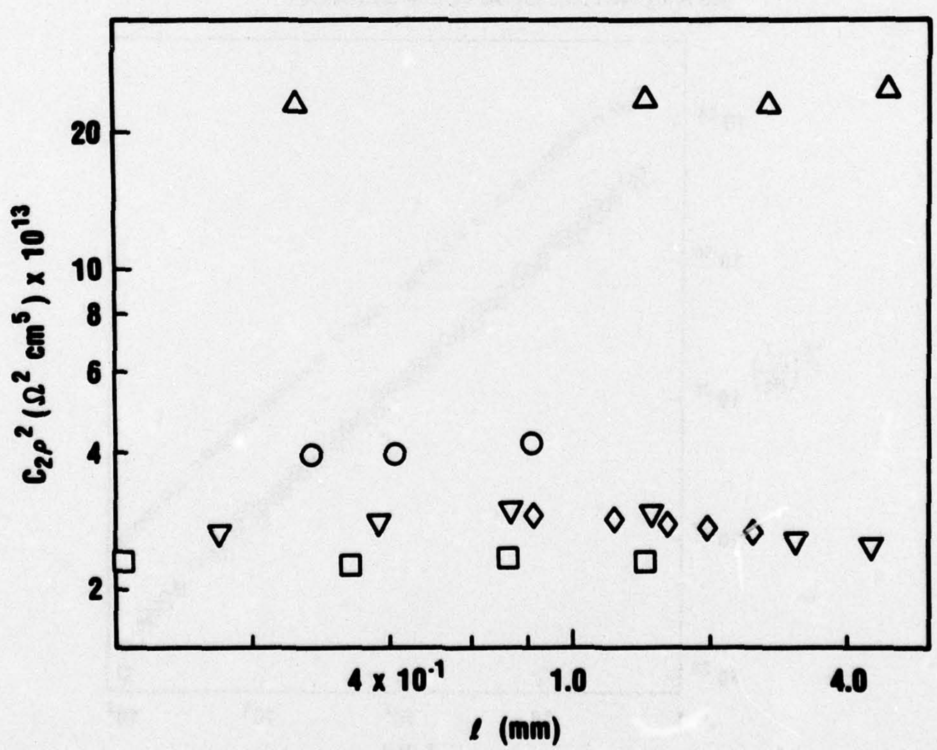

FIG. 4 SPECIFIC VOLTAGE NOISE POWER AS A FUNCTION OF SAMPLE LENGTH

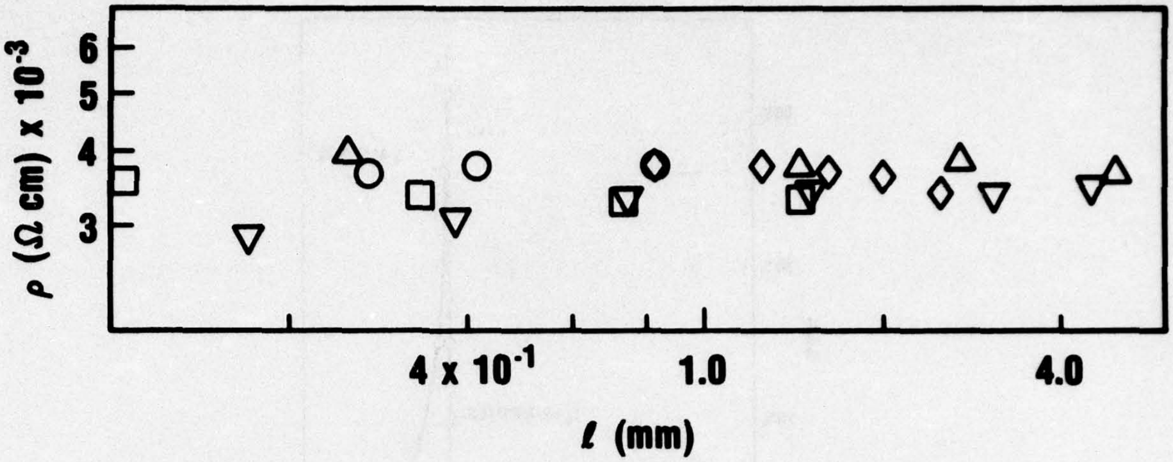

FIG. 5 RESISTIVITY VERSUS SAMPLE LENGTH

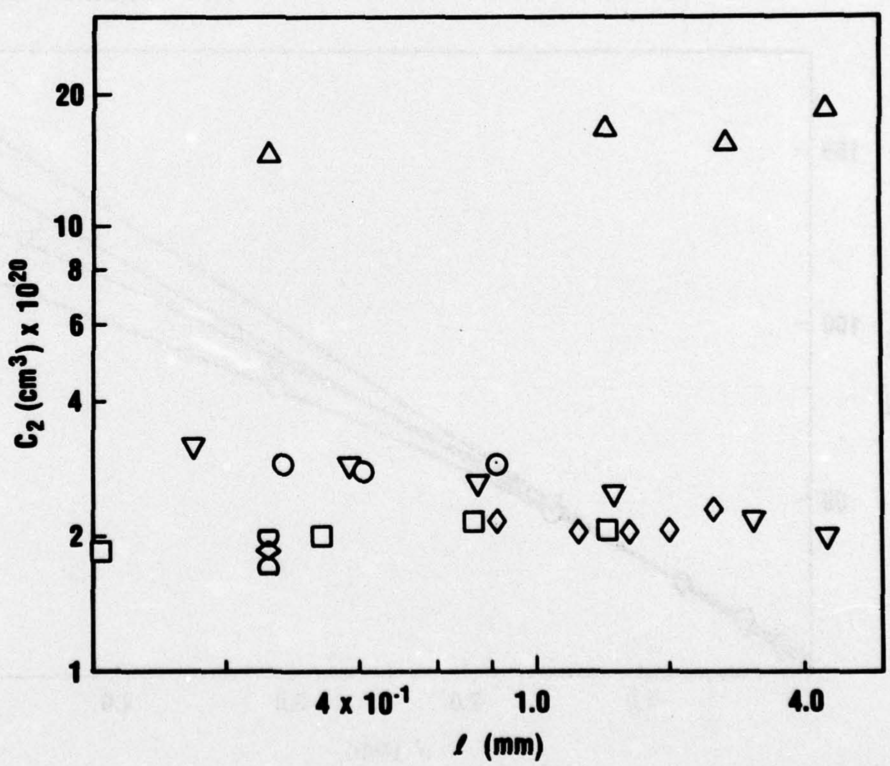

FIG. 6 THE CURRENT NOISE POWER CONSTANT OF AMORPHOUS GETE

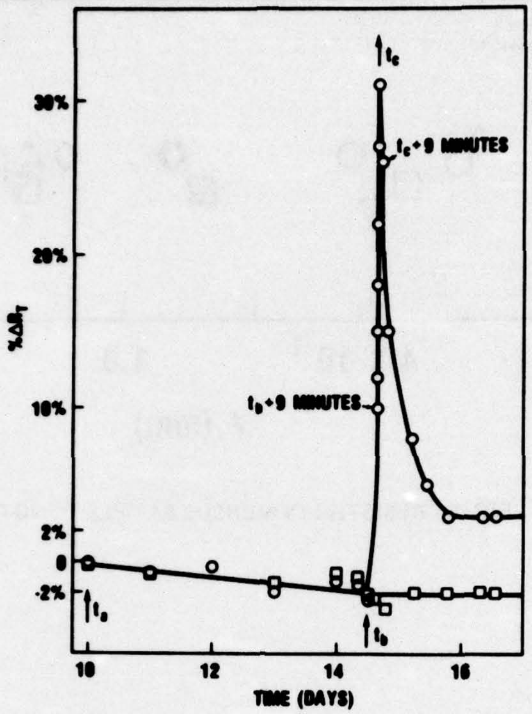

FIG. 7 EFFECTS OF AMBIENTS ON THE RESISTIVITY OF AMORPHOUS GETE FILMS

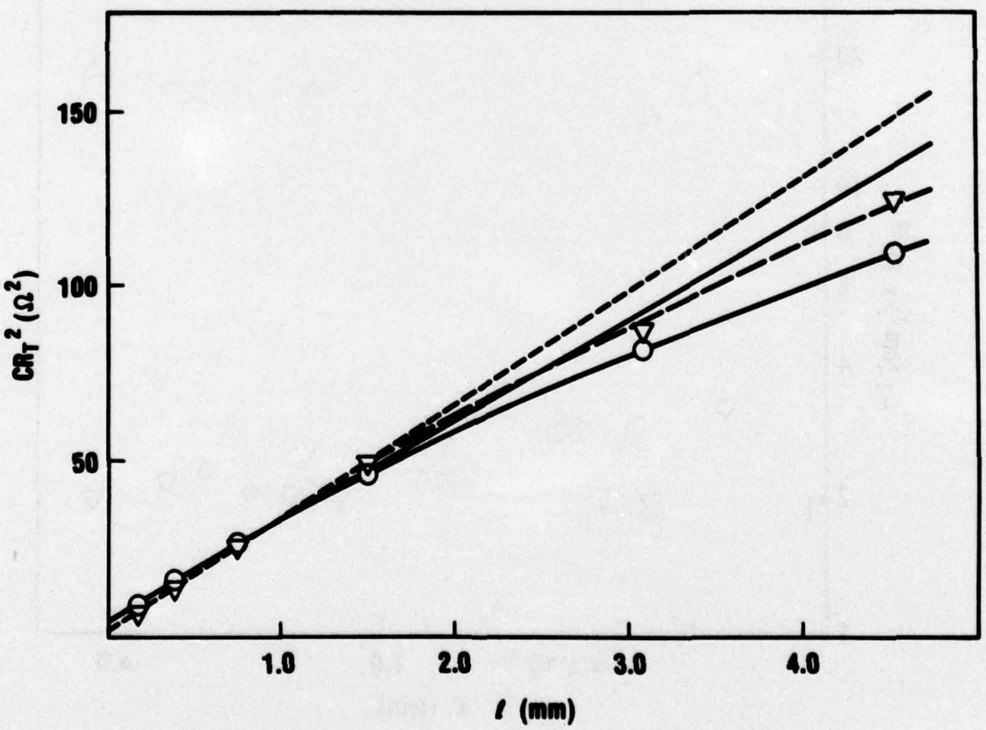

FIG. 8 VOLTAGE NOISE POWER AS A FUNCTION OF SAMPLE LENGTH OF SAMPLE # 1

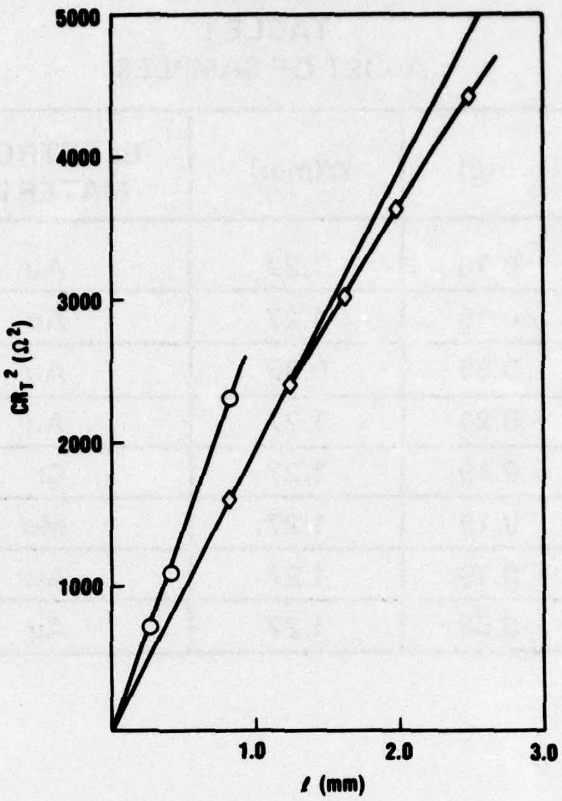

FIG. 9 VOLTAGE NOISE POWER AS A FUNCTION OF SAMPLE LENGTH OF SAMPLES # 2 AND 7

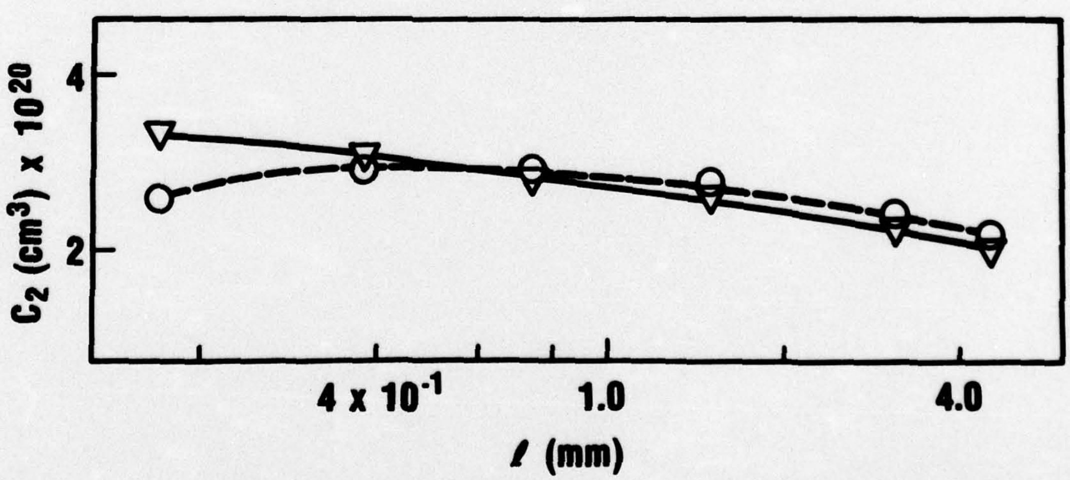

FIG. 10 THE CURRENT NOISE POWER CONSTANT OF SAMPLE # 1

TABLE I
A LIST OF SAMPLES

SAMPLE #	d(μ)	W(mm)	ELECTRODE MATERIAL	IN SITU
1	0.76	1.27	Au	YES
2	0.19	1.27	Au	YES
3	0.85	0.30	Au	YES
4	0.21	1.27	Au	NO
5	0.19	1.27	Cr	NO
6	0.19	1.27	Mo	NO
7	0.19	1.27	Au	YES
8	0.58	1.27	Au	NO

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